FINAL REPORT

EFFECTS OF SPECIMEN SIZE AND GEOMETRY EFFECTS, LOADING RATE AND MICROSTRUCTURE ON THE TENSILE FRACTURE OF SALINE ICE

PROJECT TITLE:	Effects of specimen size and geometry effects, loading rate and microstructure on the tensile fracture of saline ice
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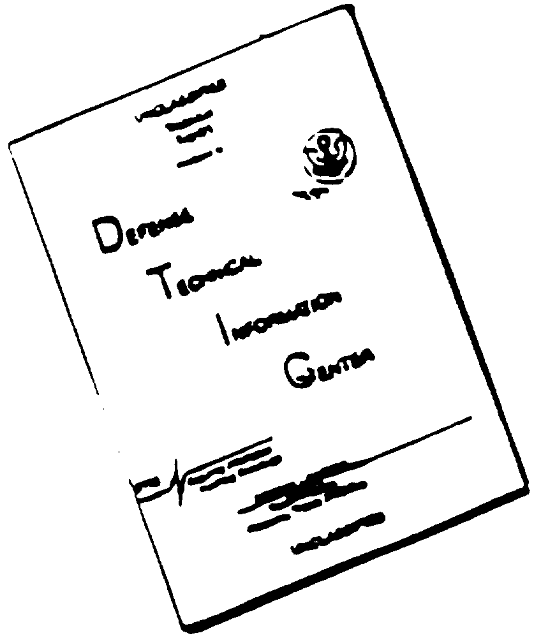

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13. ABSTRACT *(Maximum 200 words)*

This report contains the details of the experimental program on large-scale in-situ arctic sea ice tests. A total of six field trips were completed. The experiments conducted included flexure tests, fracture tests as well as tests where the ice specimen was subjected to cyclic and creep-recovery type loading. A maximum size range ratio of 1:160 was accomplished in fracture tests specifically to study the effect of variation in size. About six different geometries, (3 point bend, cantilever beam, griffith crack geometry, reverse taper geometry, square plate geometry and rectangular plate geometry) were utilized to study the effect of geometry on tensil fracture. Since the field trips occurred in three seasons, seasonal variations in ice properties including sea ice thickness variation were studied. The ice types were S1 freshwater ice, S2 freshwater ice, S2 sea ice, thin lead ice and multiyear sea ice.

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Six field trips to the arctic have been completed over the last three years as part of this project. These field trips were aimed at studying size and rate effects in sea ice. Large scale experiments coupled with small scale field and laboratory tests were completed to reach this goal. The experiments have yielded an abundance of information related to the fracture and constitutive behavior of sea ice. Table 1 summarizes the large-scale in-situ arctic experiments.

Table 1: **Summary of Large-Scale Experiments**

Date	Ice Type	Ice Thickness h(m)	Test Geometries	Size L(m)	Scale	# Tests
1/15-29, 1992 Canmore, Alberta	S1 fresh water ice	0.50	3pt[a] - FR[b] RT[c] - FR	0.50 0.34-28.64	**1:81**	4 9
4/17 - 5/7 1993 Resolute, N.W.T.	FY[d] sea ice slightly aligned	1.8	3pt - FR SQ[e] - FR SQ - FL[f]	3.0 0.5-80 3.0	**1:160**	1 15 2
11/9-19, 1993 Barrow, Alaska[1]	FY[a] sea ice Strongly aligned	0.30	SQ[b] R[g] RT[d] CORE[h]	2.5 2.5 1.0 0.36		5 1 2 4
3/9-20, 1994 Barrow, Alaska[1]	FY sea ice strongly aligned	1.5	SQ R SCB[i]	0.5-30 1.5-2.0 0.15	**1:60**	5 2 16
4/1-10, 1994 SIMI Floating Camp, Beaufort Sea[2]	FY sea ice slightly aligned	0.2-0.6 $2<h<6$	SQ MY Floe[j]	2-15 81	**1:7.5**	5 1
5/8-19,1994 Barrow Alaska[1]	FY sea ice strongly aligned	1.7	SQ R	0.25-30 8	**1:120** N/A	5 2

[1]Joint experiments with Cole, Petrenko, Shapiro and Weeks

[2]MY floe fracture experiment joint with Coon, Farmer, Pritchard and Xie

[a]3pt-Three point bend; [b]FR-Fracture; [c]RT-Reverse-tapered base-edge-cracked plates

[d]FY-First Year; [e]SQ-Square Plate (L×L); [f]FL-Flexure; [g]R-Rectangular Plate (L×2L)

[h]CORE - 0.2m diameter core, vertical, isothermal (small scale)

[i]SCB - Semi-Circular Bend Fracture/Flexure Geometry (small scale)

[j]MY Floe - Multi-Year floe

Detailed Summary of Large-Scale Experiments

Joint-Industry-Agency 'Large-Scale Ice Fracture Experiments:' A two-phase joint-industry-agency project (JIAP) was initiated in 1990 to calibrate a fracture theory for incorporation into probabalistic global ice load models. Phase I of the JIAP "Large-Scale Ice Fracture Experiments" was completed in January, 1992 near Calgary, Alberta. The primary goal of Phase I was to assess the feasibility of large-scale, full-thickness ice fracture measurements. Other objectives included: (1) Field experimentation of specimen cutting and scribing, loading systems, servo-control and instrumentation; (2) Determination of fracture toughness of full-thickness freshwater ice, global elastic modulus and scale effects.

Table 2: **Large Scale Ice Experiments @ Calgary, Alberta**

Test ID	Test Geometry	Dimensions (L x W) (m xm)	Crack Length (m)	Test Mode	Control	Ambient Air Temp. °C
GR1	Griffith	N/A	0.	gas	Load	-2.5
GR2	Griffith	N/A	0.	gas	Load	-3.0
B1	Beam	0.18x0.51	0.06	gas	Load	-2.4
B2	Beam	0.16x0.51	0.05	oil	CTOD	+5.3
B3	Beam	0.13x0.53	0.04	oil	CTOD	-1.6
B4	Beam	0.15x0.52	0.05	gas	Load	-2.1
RT1	Reversed-Taper	1.41x2.82	0.43	gas	Load	0
RT2	Reversed-Taper	0.41x0.82	0.14	gas	Load	-0.3
RT3	Reversed-Taper	4.42x8.82	1.23	gas	Load	-0.6
RT4	Reversed-Taper	0.34x0.68	0.95	gas	Load	+0.4
RT5	Reversed-Taper	1.04x2.08	0.39	gas	Load	+0
RT6	Reversed-Taper	10.36x20.72	3.12	gas	Load	+0
RT7	Reversed-Taper	3.18x6.36	0.99	oil	CTOD	0
RT8	Reversed-Taper	3.20x6.40	0.99	oil	NCTOD	-3
RT9	Reversed-Taper	28.64x57.28	8.98	gas	Load	+0
CM1	Cant. Beam	0.36x0.09	N/A	gas	Load	0
CM2	Cant. Beam	1.08x0.27	N/A	gas	Load	0

GR1,GR2,B1,B2: **Bears Paw**; B3,B4, All RT's. CM1.CM2: **Spray Lakes.**

The project began at the Bearspaw Reservoir near Calgary. Alberta. The Griffith tests and the first two beam tests were conducted there. Due to unseasonably warm temperatures. the test site was moved to Spray Lakes Reservoir in Canmore. Alberta. Ice conditions at the two sites were quite different in several respects. S2 freshwater ice existed at Bearspaw. whereas S1 columnar ice was found at Spray Lakes. Also. the ice at Bearspaw was highly fractured because of water level changes for hydropower needs. The ice at Spray Lakes had limited fractures and large areas with no visible cracks. The remaining experiments were conducted at the Spray Lakes site. Table 2 summarizes the experiments completed during Phase I of the project. at both Bearspaw and Spray Lakes.

<u>Griffith Tests:</u> Two Griffith experiments were performed at the Bears Paw Reservior (Figure

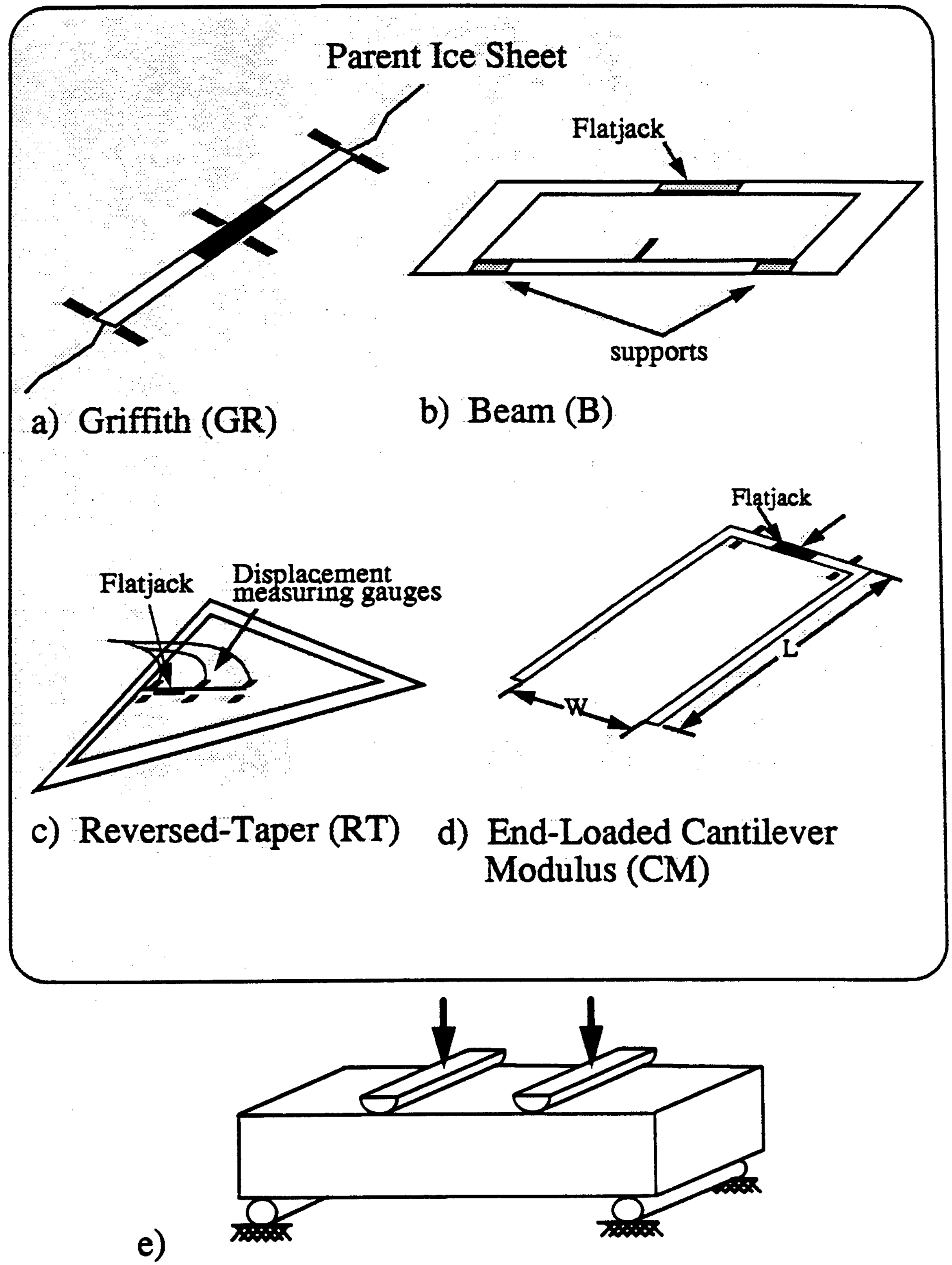


Figure 1: Test geometries: a) Griffith crack. b) Three-point-bend fracture test. c) Reversed-taper geometry. d) Cantilever beam experiment e) Small scale beam tests

1a). They consisted of simply cutting a notch in the ice sheet and inserting a flatjack. Displacement gauges were placed over the flatjack and at each of the crack tips. Stable cracking was achieved for about 3m from each crack tip.

Notched Bend Tests: The three point (3pt) bend fracture geometry shown in Figure 1b was used with the aim of investigating size effects on in–situ ice possessing a thermal gradient and a natural thermal crack density. Difficulties were encountered with the specimens freezing in place and with the sides melting – causing sloping sides unsuitable for use as loading faces. This behavior was evidenced especially in specimen B4 (Spray Lakes). Despite these problems, an initiated crack was arrested in specimen B2 (Bears Paw) by closed loop control of the servo-hydraulic system using feedback from a crack tip displacement gauge. Closed loop control of cracking had (at that time) never been performed in an ice fracture experiment in a laboratory which makes the occurrence of controlled cracking in a field experiment especially significant.

Reversed-Taper Geometry Experiments: Due to the difficulties encountered in preparing the notched bend tests, the reversed-taper geometry (RT) was adopted (Figure 1c). This geometry had been previously used for lab work at Clarkson University and proved to be very successful for promoting stable cracking (DeFranco and Dempsey, 1995). Nine RT tests, most with multiple loadings, yielded a scale range of 1:81 and included the then largest known controlled fracture test specimen ($40.5 \times 40.5 \times 0.5$m). Reducing the specimen width with increasing crack length a is conducive to slow crack extension through rapidly increasing compliance with crack extension. Tests performed with nitrogen gas generally resulted in unstable fracture. Most of the closed loop servo-controlled tests involved multiple loadings and stable crack propagation.

Cantilever Beam Experiments: An additional evaluation of specimen size on the elastic modulus was made using three in–situ cantilever beams as shown in Figure 1d. Several load/unload trials were performed on each experiment. Experiments CM1 and CM2 were successful. For CM3, the displacement gauges drifted due to the warm temperatures and wind: consequently, no useful data was obtained for this test.

Small Scale Tests: A set of small scale beam tests were completed by IMD of Canada at the site. These experiments help link the small scale lab tests with the large scale tests (Figure 1e).

Characterization: Due to the warm temperatures at the test site, no characterization could be done during the testing. A large block of the ice from Spray Lakes was shipped back to Clarkson University where detailed characterization of the ice was performed.

Phase II, Resolute Bay: Based on the success of Phase 1, large-scale fracture tests in full-thickness sea ice were conducted on Phase 2 in April, 1993 near Resolute, Northwest Territories (Kennedy et al., 1994). The tests in Resolute focused on the square plate geometry, with the successful completion of fifteen fracture and three flexure tests. Table 3 provides a summary of these experiments.

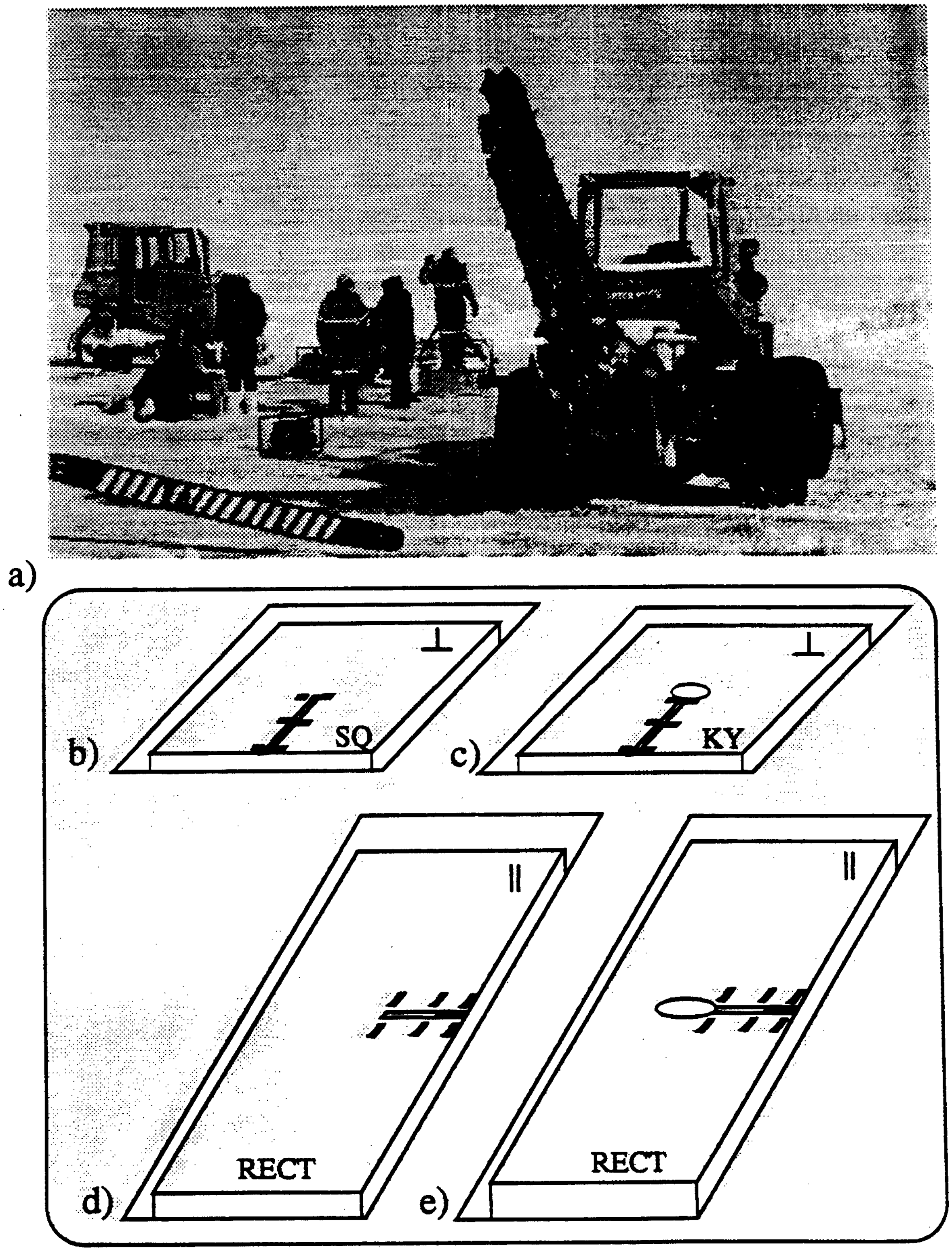


Figure 2: a) R-100 Ditchwitch for cutting out experiments: b) Square plate geometry: c) Square keyhole geometry: d) Rect. plate geometry: e) Rect. keyhole geometry

Table 3: **Large Scale Ice Experiments @ Resolute Bay**

Test ID	Test Geometry	Dimensions (L x W) (m xm)	Crack Length (m)	Test Mode	Control	Amb. Air Temp. °C
SQ1	Square	1.0x1.0	0.3	gas	Load	-9
SQ2	Square	0.9x0.9	0.28	gas	Load	-13
SQ3	Square	10.0x10.0	3.0	gas	Load	-13
SQ4	Square	10.0x10.0	5.02	gas	Load	-13
SQ5	Square	30.0x30.0	9.0	gas	Load	-13
SQ6	Square	30.0x30.0	9.0	gas	Load	-14
SQ7	Square	30.0x30.0	9.0	gas	Load	-15
SQ8	Square	3.0x3.0	0.9	gas	Load	-15
SQ9	Square	3.0x3.0	0.9	servo	CMOD	-3
SQ10	Square	0.5x0.5	0.26	gas	Load	-3
SQ11	Square	30.0x30.0	9.0	servo	NCTOD	-14
SQ12	Square	0.5x0.5	0.25	servo	CMOD	-14
SQ13	Square	80.0x80.0	24.0	gas	Load	-12
SQ14	Square	30.0x30.0	9.0	servo	NCTOD	-12
SQ15	Square	3.0x3.0	0.9	servo	CMOD	-17
FL1	Beam	1.0x0.25	no crack	gas	Load	-17
TE1	Keyhole	3.0x3.0	1.5	servo	Load	-6
TE2	Keyhole	3.0x3.0	1.5	servo	Load	-6

Square Plate Experiments: The square plates tested ranged from (0.5 × 0.5 × 1.8m) to (80 × 80 × 1.8m) covering a size range of 1:160. The ice was 1.8m thick so a large DitchWitch, shown in Figure 2a, was necessary to cut out the plates. It was able to create a 15 cm wide slot between the test piece and the parent ice sheet. This limited refreezing of the cut, providing the group time to clean the slush from the cut. A second smaller Ditchwitch was then used to cut the crack in the specimens. This machine cut a notch 1.6 cm wide, enough to insert the loading device, the flatjack. Because it was a narrow cut, it had to be constantly cleaned to prevent refreezing. Both rate and size effects were examined. The loading was achieved by means of a flatjack inserted into the precut crack in the specimen. On the surface of the specimen, the crack opening displacements were measured at three points: the crack mouth (CMOD), the crack tip (CTOD), and at a point in between (COD). At each point, two displacement gauges were used, an LVDT and a KAMAN non-contacting displacement gauge. The KAMAN gauge had a finer resolution, but went out of range much earlier. As the crack opened, the KAMAN gauge would go out of range and the LVDT continued measuring, providing a continuous record of the crack activity. This was necessary for capturing the unloading curve immediately following fracture. Figure 2b shows the test setup for a typical square plate fracture test. All gauges were connected to two different digital recording devices, two 486 computers. This method of two backups ensured that no data was lost. One 486 computer was used for real time viewing of the gauge responses and slow data acquisition. The other computer was devoted to high speed data aquisition.

The flatjack was pressurized by either a gas or servo-controlled oil system. The pressure in the flatjack was proportional to the pressure applied to the ice, and was calculated through lab calibration of the flatjack. When using air, the load applied to the ice was controlled. Typically, these were longer tests, running for at least five minutes. This system was capable of introducing prescribed unloadings at various times in the loading. The hysteresis loops in the Load vs COD plots provide constitutive information as well as information necessary to calculate internal friction values. Servo controlled tests used displacement feedback for control. These were faster tests, usually taking less than one minute to fracture.

Flexure Experiments: The testing of in-situ flexure beams proved to be a difficult task in Phase I. One flexure beam was tested in Phase II. The test was successful, but required an excessive amount of preparation. It was found that test specimens using self-equilibrated loading (the RT on Phase I and the square plate on Phase II) were inherently easier to setup, requiring minimal preparation. This provoked the use of the square plate keyhole geometry (Figure 2c). This was a flexure test similar to the square plate fracture tests, except that a 20cm hole was bored at the crack tip. The displacement gauges were placed at points on the crack, similar to the fracture tests.

High Speed Video: Bob Gagnon of CNRC filmed the cracking events in the large scale fracture tests.

Acoustics The acoustic signals resulting from the cracking events were recorded by Xie and Farmer from the Institute of Ocean Sciences. They deployed two hydrophones with a sampling frequency of 44.1kHz. These devices allowed acoustical measurements of propagation speeds of developing ruptures and acoustic radiation levels due to micro-cracking as the tensile load was increased.

Small Scale Tests: IMD/NRC of Canada carried out experiments on the flexural strength of the ice for different sizes, depths, and orientations (Figure 2d). A series of small scale fracture toughness measurements with a range of parameters similar to those of the strength tests were also performed.

Characterization: A tent was set up at the site with all the equipment necessary for the full characterization of the ice. Characterization of the full thickness of the ice sheet was completed as well as salinity and density profiles.

Sea Ice Mechanics Initiative (SIMI) - Barrow, AK: In order to track the seasonal evolution of the mechanical and physical properties of first year sea ice, three field trips were conducted at Barrow, Alaska: November 9–19, 1993, March 9–20 and May 8–19 of 1994. This was a joint effort including Weeks, Shapiro, and Byers from the University of Alaska at Fairbanks (UAF), Dave Cole from CRREL, New Hampshire, and our group from Clarkson University. A total of thirty large scale tests were completed covering a wide range of sizes, temperature profiles, and loading paths. Each set involved a large scale in-situ (full ice thickness) matrix of experiments and a complementary small scale (partial thickness) matrix of experiments. The ice conditions encountered at Barrow were very interesting: that is, the sea ice was strongly aligned, and thus, in addition to the salinity, grain size and thermal profile there was this additional important microstructural feature to incorporate. In all these experiments, a computer-controlled flatjack loading system was employed to load the ice along preset load paths recording both load and deformation. Issues examined included the effects of size, rate, load path (monotonic, cyclic and creep recovery) and geometrical test orientation vs c-axis alignment. Figure 3a shows the schematics of the various load paths. On each trip, detailed characterization and micrography was carried out by Cole

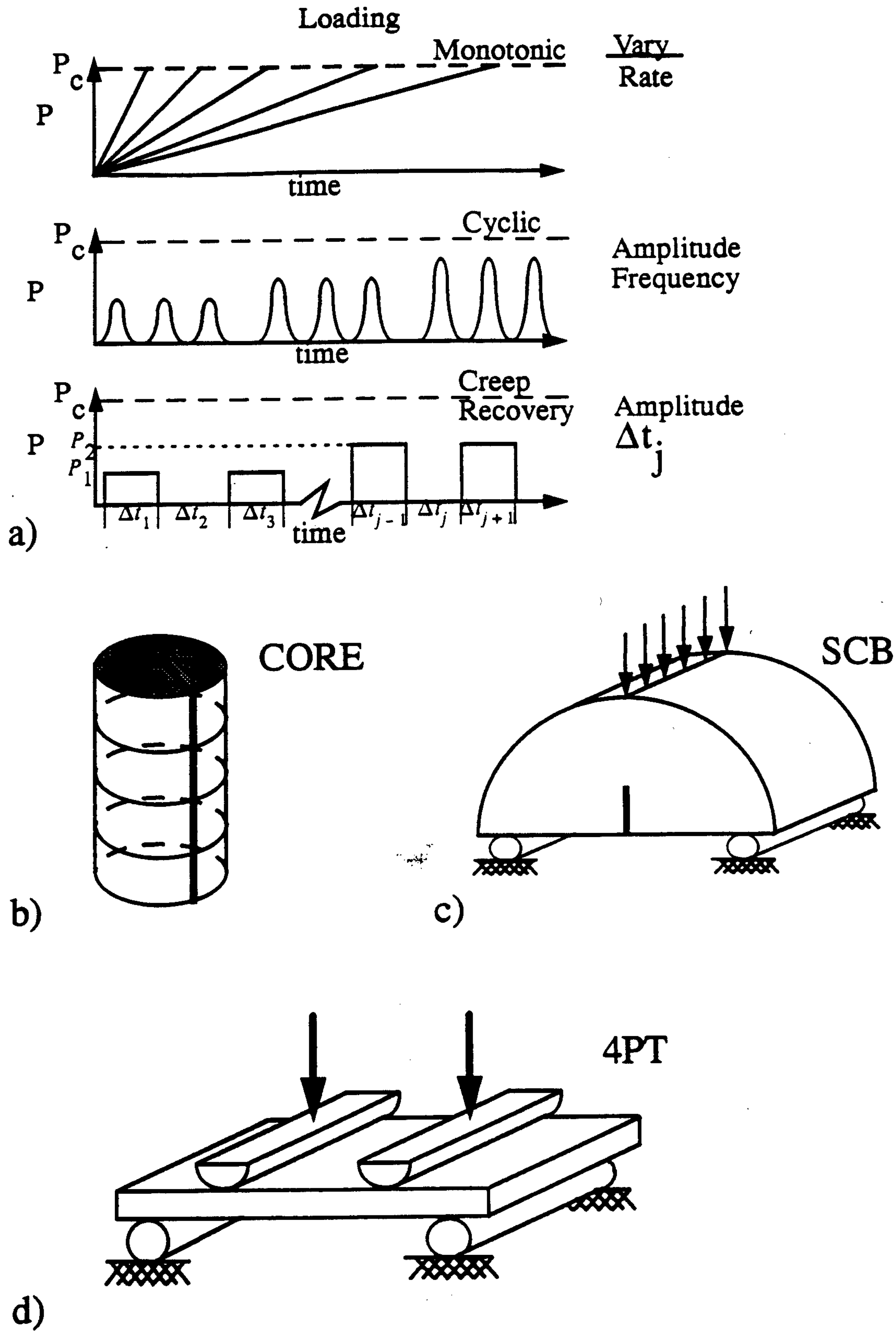


Figure 3: a) Schematic of various load paths b) Core geometry: c) SCB fracture geometry: d) Four-point-bend flexure geometry

Table 4: **Large Scale Ice Experiments @ Barrow, AK: November 9-19**

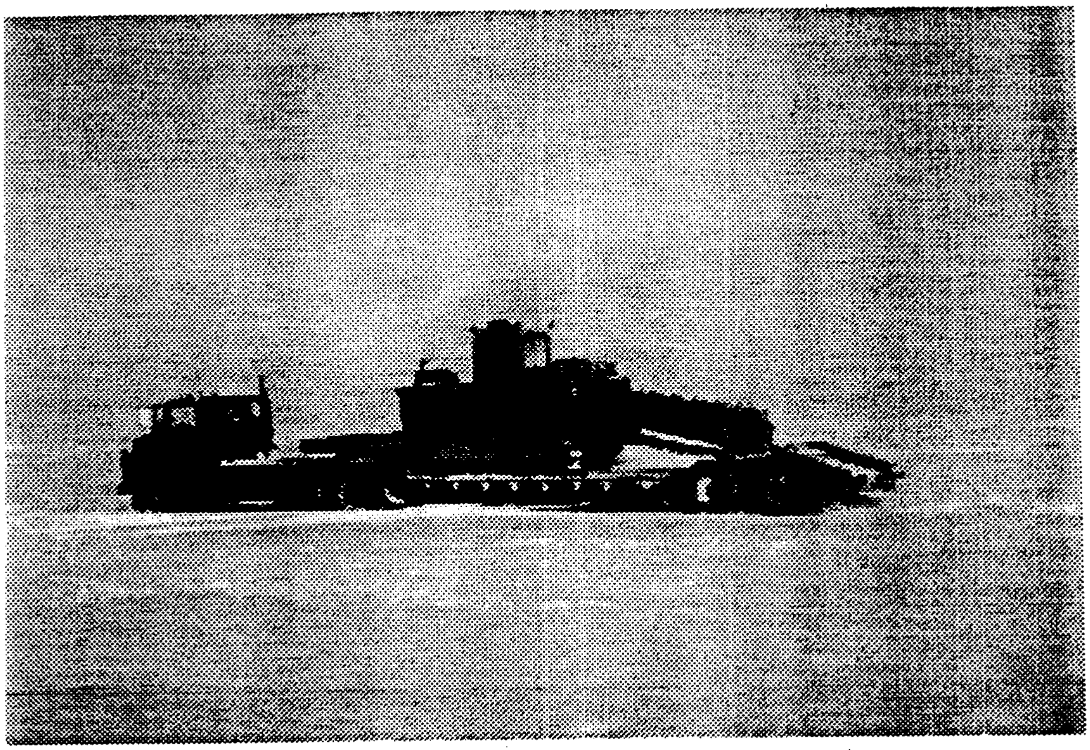
Test ID	Test Geometry	Dimensions (L x W) (m xm)	Crack Length (m)	Test Mode	Failure	Control
SPF1	Square	2.5mx2.5m	0.75	Fracture	Easy	Cyclic/Ramp
SPF2	Square	2.5mx2.5m	0.75	Fracture	Easy	Cyclic/Ramp
SPF3	Square	2.5mx2.5m	0.75	Fracture	Easy	CMOD-Ramp
SPF4	Square	2.5mx2.5m	0.75	Fracture	Hard	Cyclic/Ramp
SPF5	Rectangle	2.5mx5.0m	1.25	Flexure	Hard	Cyclic/Ramp
SPF6	Square	2.5mx2.5m	0.75	Flexure	Easy	Fast Ramp
SPF7	RT	1.0mx2.0m	0.3	Fracture	Easy	Fast Ramp
SPF8	RT	1.0mx2.0m	0.3	Fracture	Hard	Fast Ramp
CORE1	Core	0.36mx0.2mϕ	0.1	Fracture	Easy	Fast Ramp
CORE2	Core	0.36mx0.2mϕ	0.1	Fracture	Easy	Fast Ramp
CORE3	Core	0.36mx0.2mϕ	0.1	Fracture	Hard	Fast Ramp
CORE4	Core	0.36mx0.2mϕ	0.1	Fracture	Hard	Fast Ramp

Table 5: **Large Scale Ice Experiments @ Barrow, AK: March 9-20**

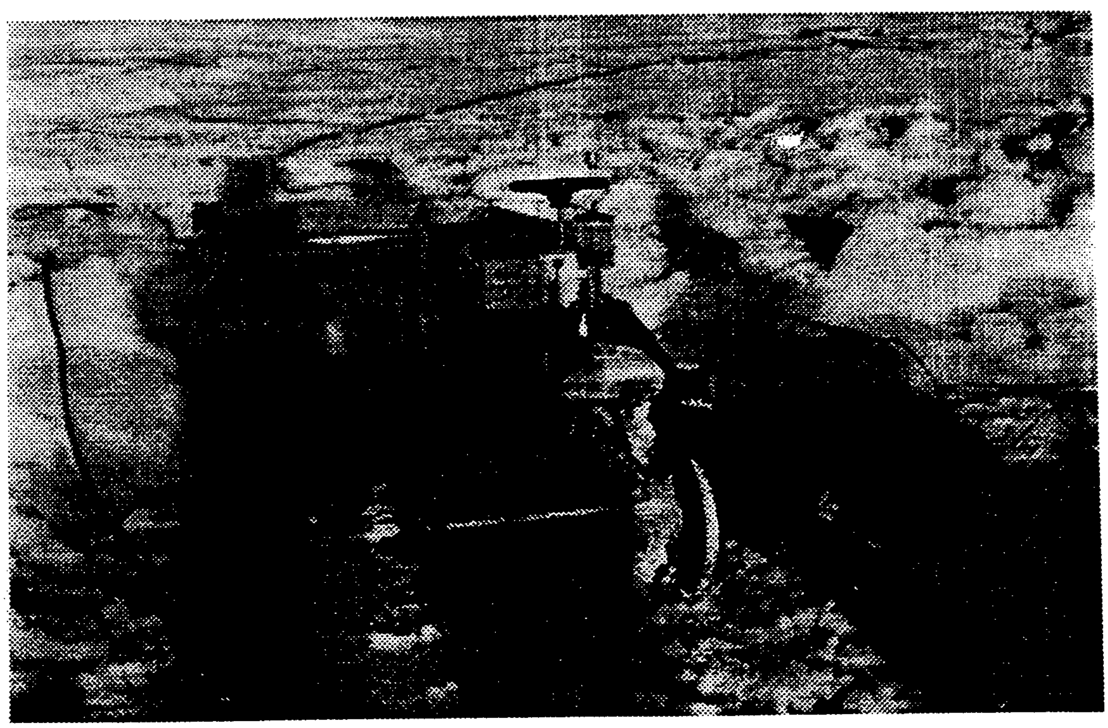
Test ID	Test Geometry	Dimensions (L x W) (m x m)	Crack Length (m)	Test Mode	Failure	Control
SQPL1	Square	1.5mx1.5m	0.45	Fract.	Easy	Ramp
SQPL2	Square	1.5mx1.5m	0.45	Fract.	Easy	Ramp
SQPL3	Rect.	3.0mx1.5m	0.45	Fract.	Hard	Ramp
SQPL4	Square	2.5mx2.5m	0.75	Fract.	Easy	Mono/Ramp
SQPL5	Square	2.0mx2.0m	0.6	Fract.	Easy	Ramp
SQPL6	Rect.	4.0mx2.0m	0.6	Fract.	Hard	Ramp
SQPL9	Square	30.0mx30.0m	9.0	Fract.	Easy	Cyc/CR/Ramp
SQPL10	Square	0.5mx0.5m	0.25	Fract.	Easy	Cyclic
SCB	SCB	0.15mx0.2mϕ	0.06	Fract.	H/E	Cyc/Ramp

Table 6: **Large Scale Ice Experiments @ Barrow, AK: May 8-19**

Test ID	Test Geometry	Dimensions (L x W) (m x m)	Crack Length (m)	Test Mode	Failure	Control
SQ1	Square	16.0x16.0	4.8	Fracture	Easy	CR/Ramp
SQ2	Square	4.0x4.0	1.2	Fracture	Easy	Cyclic/Ramp
SQ3	Rect	8.0x16.0	2.4	Fracture	Hard	CR/Cyc/Ramp
SQ4	Rect	8.0x16.0	3.0	Fracture	Hard	CR
SQ5	Square	1.0x1.0	0.29	Fracture	Easy	CR/Ramp
SQ6	Square	0.25x0.25	0.13	Fracture	Easy	CR
SQ7	Square	30.0x30.0	9.0	Fracture	Easy	Cyc/CR/Ramp



a)



b)

Figure 4: Large-scale ice cutting machinery a) 30 ton Ditchwitch: b) Specially designed cutting machine

from CRREL in a cold room located near the test site.

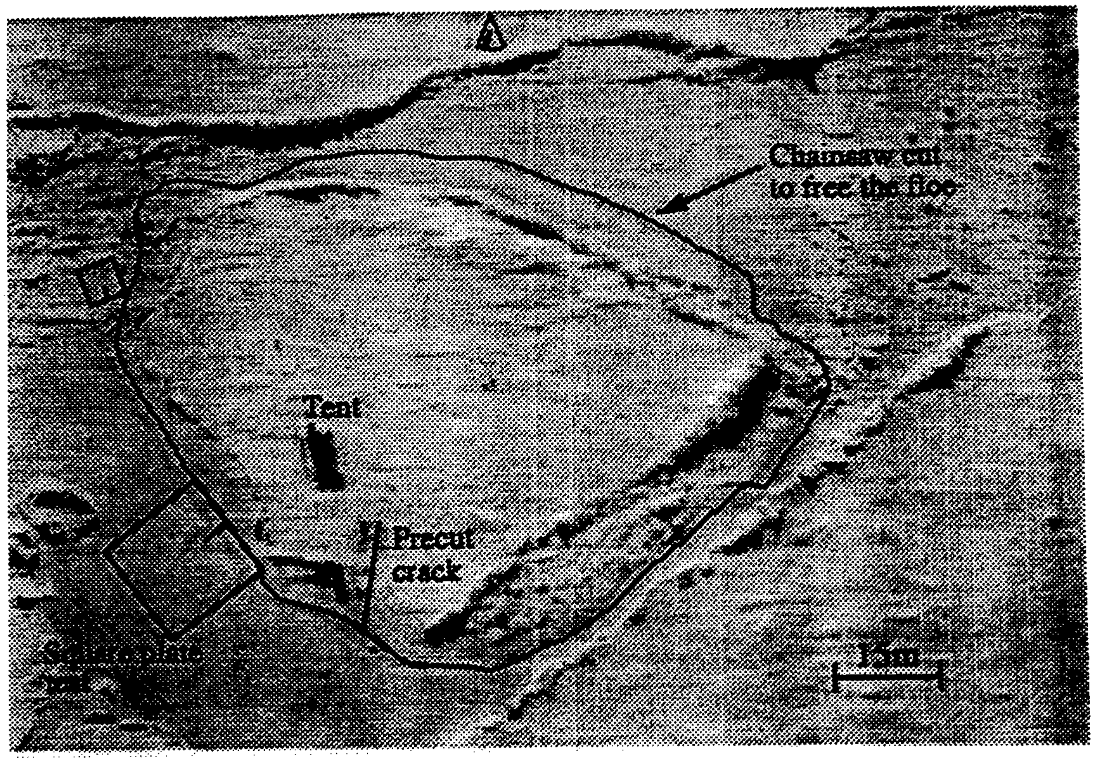
November 9–19: At this time, the ice was about 30cm thick and showed a strong c-axis alignment. Because of the strong c-axis alignment, the test plan was modified and tests with the crack propagating parallel (hard fail, $\|$) and perpendicular (easy fail, $\perp$) to the c-axis were conducted. Table 4 presents the large scale tests completed on the first trip to Barrow, AK. Due to the success of the square plate geometry in Phase II, it was used again. Unfortunately when testing SPF4, a square plate with the precut crack in the hard fail direction, the crack still chose to propagate in the easy fail direction, resulting in a strength failure. To overcome this problem, a rectangular geometry was chosen, with a width twice that of the length. This geometry was tested in SPF5 and proved to be successful. The flexure tests were accomplished by drilling a hole at the tip of the crack which was precut in the square or rectangular sample. The RT geometry used in Phase I was also tested. This geometry was able to overcome the crack's tendency to propagate in the easy fail direction when testing in the hard fail plane. Petrenko from Dartmouth was present for these experiments to study the electromagnetic emissions from the fractures. Foil electrodes were placed on either side of the predicted crack path and were able to measure the velocity of the propagating cracks.

Small Scale Tests: Full depth cores were tested by cutting a crack from the side to the center of the core as shown in Figure 3b. A small flatjack was then put in the crack and the core was split in half. Each half was then used to make SCB specimens shown in Figure 3c. These tests show the variation in strength with respect to depth and orientation. Also, small plates subjected to four point bending were tested (Figure 3d). All small scale experiments were done under isothermal conditions by Shapiro and Weeks from UAF. These tests provided the link between large scale tests and small scale laboratory experiments.

March 9 to 20: At this time, the ice sheet was approximately 1.7m thick. The average air temperature was -25°C, creating a large temperature profile. Because of the ice thickness, the samples had to be cut with a ditchwitch (Figure 4a) and a specially designed saw (Figure 4b). To achieve similar aspect ratios (width to thickness) as compared to the first trip, larger samples were required. The tests conducted on the second trip are summarized in Table 5. A total of 10 tests were completed covering a size range of 1:30 with the largest being a 30m x 30m square plate. High speed measurements of the electromagnetic emissions (EME) were recorded providing quantitative information on the cracking dynamics.

Small Scale Tests: In addition to the large scale matrix, a set of small scale experiments were completed at the site. It consisted of sixteen semi-circular-bend (SCB) tests, 8 with the crack parallel to the c-axis (hard fail) and 8 with the crack parallel to the basal plane (easy fail). Each test was at a subsequently lower depth in the ice sheet, providing information on the strength relative to the depth. All of the SCB tests were conducted in a small field testing apparatus under isothermal conditions.

May 8 to 19: By this time in the season, the ice was still about 1.7m thick but had a near vertical temperature profile through the thickness. Again, the Ditchwitch and the special crack cutting machine were required. Table 6 presents the list of the tests conducted on the third trip. To compare with the largest size on the previous trip, another 30m x 30m plate was tested. Similar loading sequences were applied to both specimens in order to determine the effect of the temperature profile on the strength and cracking behavior. Schapery from the University of Texas visited the site and provided useful insight on applying load recovery sequences to determine the viscoelastic behavior of the sea ice. Cole from CRREL employed an acoustic emissions (AE) monitoring system on this trip. Two ultrasonic transducers were



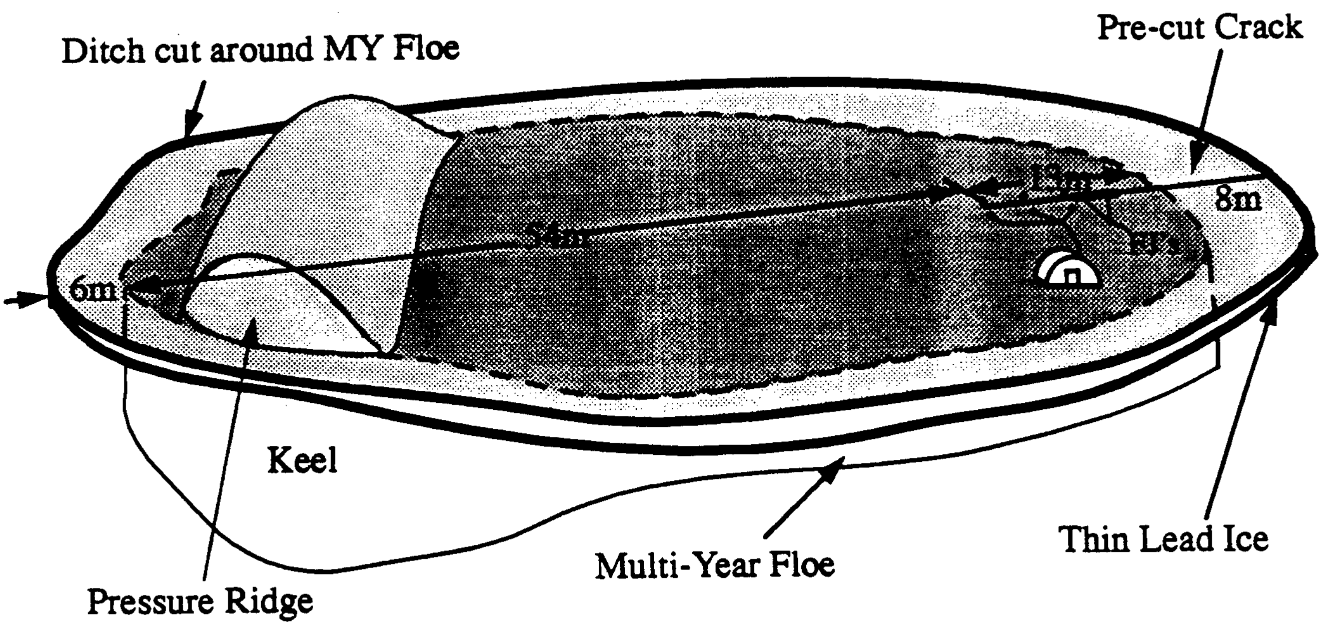


Figure 5: Multi-Year ice floe split at the SIMI Camp, Beaufort Sea

Table 7: **Large Scale Ice Experiments @ the Floating SIMI Camp, Beaufort Sea**

Test ID	Test Geometry	Dimensions (L x W) (m x m)	Crack Length (m)	Test Mode	Thickness (m)	Control
SQ1	Square	2.0x2.0	0.74	Fracture	0.20	Ramp
SQ2	Square	3.66x3.66	0.43	Fracture	0.20	Ramp
SQ3	Square	2.44x2.44	0.84	Fracture	0.60	Cyc/Ramp
SQ4	Square	4.88x4.88	0.84	Fracture	0.60	CR/Cyc/Ramp
SQ5	Square	15.0x15.0	3.29	Fracture	0.20	CR/Ramp
FLOE		80m dia.	9.0	Fracture	4.0-5.0	Cyc/Ramp

frozen to the surface slightly ahead and to either side of the crack tip. This system provided useful information on microcrack nucleation in the crack tip vicinity, giving a clear indication of the threshold load needed for the onset of microcracking activity.

Small Scale Tests: In addition to the large scale tests, lab sized specimens were tested at the site. SCB samples were tested as on the second trip. Three full depth cores were also shipped back to Clarkson University for continued testing at isothermal conditions. SCB as well as tension experiments were completed and a full characterization of the sheet was done to see if the ice morphology had changed.

FLOATING SIMI CAMP, BEAUFORT SEA: In the spring of 1994, the PI participated in a Sea Ice Mechanics Initiative (SIMI) project geared toward studying the mechanics of sea ice. A total of seven fracture tests were done at the SIMI floating camp in the Beaufort Sea. Table 7 has a summary of the experiments conducted at the camp.

Square Plate Tests on Lead Ice: Five square plate goemetry tests were completed on lead ice with thicknesses ranging from six inches to two feet. Most of the square plates were subjected to an extensive set of cyclic and creep recovery sequences at relatively low loadings. A controlled monotonic load ramp was applied to fracture the plates. As with previous field trips, displacement gauges were placed at chosen locations on the ice surface to measure the crack opening displacements. Blocks of ice from several of the experiments were shipped back to Clarkson University for full characterization.

Splitting of a Multi-Year Floe: The most significant field achievement of the PI was the successful splitting of a 80m diameter multi-year ice floe shown in Figure 5. The surrounding lead ice was double cut with chainsaws and the pieces were removed. This created about a one foot gap around the floe to ensure it was not subject to any confining forces. A crack about 10m long was then cut in the floe. Due to the limitations of the saw, the crack was only cut partially through the thickness. Low level cyclic loading was first applied to force the crack to propagate down through the thickness. The floe was then loaded to failure. Acoustic signals were recorded by Xie and Farmer and the MIT/WHOI group. Results from Xie and Farmer show the cracking as a function of time, verifying the splitting. In addition, crack velocities and crack paths were determined.

Findings to date

Phase I - Alberta, Canada: The in-situ experiments were all done at very warm temperatures, temperatures at which laboratory experiments are essentially impossible. A large size range was completed for very large macrocrystalline freshwater ice. It was very interesting to see that even short term loadings to failure exhibited nonlinearity. Through modelling efforts, the process zone was found to be very small for all sizes. Accordingly, the apparent size effect is due not to growth in the process zone size but rather specimen size vs. grain size (polycrystallinity effect).

Phase II - Resolute, Canada: A very large size range on thick (1.8m) slightly aligned first year sea ice was completed. Analysis of the experiments has shown a significant influence of bulk viscoelastic as well as rate dependent process zone behavior. It was also found that current size effect laws are not immediately applicable.

Barrow, Alaska: A large amount of data was collected for experments covering a large size range with variations in thickness, thermal profile, grain size and salinity. Cyclic as well as creep recovery loading sequences were applied to many of the experiments. This is very important for extracting the constitutive behavior of the sea ice necessary for modelling efforts. In addition, good fracture/electromagnetic information was obtained which is very useful for determining the cracking behavior. At present, little analysis of these experiments has been done.

SIMI Camp, Beaufort Sea: The cracking of a 80m diameter multi-year floe was a significant accomplishment on this trip. Xie and Farmer (1995) deployed a series of hydrophones around the floe, capable of tracking the cracking events. Interactions with Yunbo Xie have enabled us to correlate our load and displacement records with his record of the crack tip position. In addition to the floe, square plate tests were conducted on the thin lead ice. Although no analysis has been done, blocks of ice were shipped back to Clarkson University where a thorough characterization was done. It showed a slight alignment in the c-axis of the thin first year ice.

Analysis and Publication Plans

Analysis of the the field tests is underway at Clarkson University. In addition, characterization and testing of cores and blocks from the trips sent to Clarkson University is being done. Modeling efforts are in progress as well as checking the validity of various size effect laws. Interactions with Prof. Schapery (University of Texas, Austin) are underway for analyzing the creep recovery records as well as developing a constitutive model for sea ice incorporating a viscoelastic component. Interactions with Dave Cole include discussions related to sea ice micrography and implementation of his anelastic straining model. Interactions with Xie and Farmer and Petrenko will continue in an effort to relate their cracking information with our load and displacement records. Interactions with Shapiro and Weeks on the topics of small scale tests and ice characterization will continue. Following is a list of topics for future publications and collaborations related to results from the SIMI projects:

- Evaluation of existing size effect laws.
- Development of rate-independent process zone model.
- Development of rate-dependent process zone model.
- Development of process zone modeling incorporating bulk nonlinear viscoelastic de-

formation.

- Evaluation of stress-separation law dependencies on influences such as size and rate.
- Do the fracture properties at large scale differ significantly from those at small scale?
- Can laboratory-scale testing be used to predict properties at large scale?
- What particular problems are faced with large scale testing?
- Comparison of acoustic and electromagnetic crack position data with process zone modeling (Xie and Farmer, Petrenko).
- Comparison of acoustic energy signatures with process zone energy predictions (Xie and Farmer).
- Publish characteristics of small-scale and large scale data (Cole. Shapiro, Weeks)

Following is a list of related publications in print or to be submitted:

"Joint Sea Ice Experiments at Barrow. Alaska," D.M. Cole. J.P. Dempsey. R.M. Adamson. L.H. Shapiro, W. Weeks, C. Byers, V. Petrenko. O.V. Gluschenkov, in *ICE MECHANICS-1995*, ASME AMD-Vol. xxx (in preparation).

"Fracture analysis of semi-circular and semi-circular-bend geometries," R.M. Adamson, J.P. Dempsey and S.V. Mulmule, in *International Journal of Fracture* (submitted for publication, 1995).

"Large-scale ice fracture experiments in Alberta and at Resolute," J.P. Dempsey, R.M. Adamson, S.V. Mulmule, S.J. DeFranco and Y. Xie, in *ICE MECHANICS-1995*, ASME AMD-Vol. xxx (in preparation).

"Large-scale ice fracture experiments at Barrow and on the SIMI Camp," R.M. Adamson, J.P. Dempsey, S.V. Mulmule and Y. Xie, in *ICE MECHANICS-1995*. ASME AMD-Vol. xxx (in preparation).

J. P. Dempsey, Z. P. Bazant, Y. D. S. Rajapakse. S. S. Sunder, *ICE MECHANICS-1993*. ASME AMD-Vol. 163.

J. P. Dempsey and Y. D. S. Rajapakse, *ICE MECHANICS-1995*, ASME AMD-Vol. xxx (in preparation).

"Laboratory and field-scale fracture of an analogue quasi-brittle material: ice," J. P. Dempsey and S. J. DeFranco. in *Size Effect in Concrete Structures*. H. Mihashi. H. Okamura and Z. P. Bažant, E & FN SPON (Chapman and Hall) (1994) 151–158.

"Splitting of Ice Floes," J.P. Dempsey, S.J. DeFranco. D. Blanchet and A. Prodanovic. in *12th POAC Conference*. Vol. 1, 17–22. 1993.

"Large-Scale Ice Fracture Experiments." K.P. Kennedy. D. Blanchet. A. Prodanovic. J.P. Dempsey, S.J. DeFranco. P.A. Spencer and D. Masterson. in *12th POAC Conference*. Vol. 2, 527–536, 1993.

"Large-scale ice fracture experiments: Phase 2." K.P. Kennedy, K.J. Mamer, J.P. Dempsey, R.M. Adamson, P.A. Spencer and D.M. Masterson, in *IAHR 94: Proceedings of the 12th International Symposium on Ice*, Trondheim, Sweden, Vol. 1, pp 315-324, 1994.

"Fracture resistance determination of freshwater ice using a chevron notched tension specimen" L. M. Stehn, S. J. DeFranco and J. P. Dempsey, in *International Journal of Fracture* **65** 313–328, 1994.

"Specimen geometry effects on the fracture of warm pond (S1) ice," L.M. Stehn, S.J. DeFranco and J.P. Dempsey, in *ASCE Journal of Engineering Mechanics* **121**, 16–25, 1995.

"Orientation effects on the fracture of pond (S1) ice" L.M. Stehn, S.J. DeFranco and J.P. Dempsey, in *Engineering Fracture Mechanics* (in press).

"Fracture Analysis of base-edge-cracked reverse-tapered plates," J.P. Dempsey, R.M. Adamson and S.J. DeFranco, in *International Journal of Fracture*, (in press).

"A grain multiplication mechanism for the formation of transition zones in first year sea ice," Y. Wei, M. Johnston and J.P. Dempsey, in *Cold Regions Science and Technology* (in press).